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## Summary and Conclusions

The present research work dealt with the investigations of bathymetry, gravity and seismic reflection data of three important aseismic ridges: Comorin Ridge, 85°E Ridge and Ninetyeast Ridge, of the northeastern Indian Ocean for determining the internal structure and isostatic compensation mechanisms. The study brought out important constraints with regard to crustal architecture, isostatic compensation mechanisms and evolutionary models for all three aseismic ridges, and the results provided new insights to the understanding of geodynamics of the northeastern Indian Ocean in a broad perspective. Summary of the work reported in this thesis and the conclusions arrived at are as follows.

### 7.1 The Structure and isostatic model of the Comorin Ridge

The Comorin Ridge is one of the least studied aseismic ridges in the Indian Ocean, in spite of its location close to the Indian Continental Margin. Ship-borne bathymetry, gravity and magnetic data of the Comorin Ridge were investigated to map the ridge extent, morphology and its gravity anomaly signatures. Further, the structure and isostasy of the Comorin Ridge were studied using transfer function technique and forward modeling of gravity and bathymetry data. The important conclusions derived from this study are as follows.

1. The Comorin Ridge extends for about 500 km in NNW-SSE direction in north central Indian Ocean, close to the southern tip of India and western continental margin of Sri Lanka. The ridge topography has variable reliefs along its strike and uneven gradients on both sides of the ridge flanks. The southern part of the ridge (between 1.5°N and 3°N) has an elevation of up to 0.5 km from the adjacent seafloor of about 4 km deep; in the central part (between 3°N and 5°N) the ridge has a maximum elevation of up to 1 km from the surrounding water depths ranging from 3 to 4 km, and in the north (between 5°N and 6.5°N) the ridge elevates mostly on eastern side of the ridge, ranging from 0.4 to 0.7 km from adjacent water depths of about 2.5 km. Across the

southern part of the ridge the western flank extends for more than 100 km with relatively smooth gradient and the eastern flank steeply deepens with a scarp of about 1.2 km within a horizontal distance of about 50 km.

2. Geophysical profile data of the Comorin Ridge show that the ridge is associated with relatively low-amplitude gravity anomalies of about 25 mGal in southern part ( $1.5^{\circ}\text{N} - 5^{\circ}\text{N}$ ) and 30 mGal in northern part ( $5^{\circ}\text{N} - 6.5^{\circ}\text{N}$ ) compared to its elevations. There is a significant inference to note that a less-raised north part of the ridge is associated with relatively higher (30 mGal) gravity anomaly, suggesting that this part of the ridge is relatively less compensated in comparison to that of south part of the ridge. On the eastern flank of the ridge the gravity profiles data show a sudden regional shift in anomaly by about 50 mGal, which may indicate the location of Continent-Ocean Boundary (COB) on the western continental margin of Sri Lanka. The seafloor spreading-type magnetic anomaly 34 is identified on profiles V2902-a and C1215, besides there are other anomalies with short-wavelength and low-amplitude observed on oceanic crust evolved during the period of pre anomaly 34, that is during the Cretaceous Magnetic Quiet Period. It is also observed that the Comorin Ridge is not associated with any specific magnetic anomaly signatures.
3. Admittance analysis of the Comorin Ridge suggested that the southern part of the ridge (south of  $5^{\circ}\text{N}$ ) is compensated with Airy model or local compensation with an elastic plate thickness ( $T_e$ ) of about 3 km and crustal thickness ( $t$ ) of 15-20 km, while the northern part is compensated with flexural plate model with an elastic thickness of about 15 km. Two-dimensional gravity forward model studies suggest that the crust beneath the southern part of the ridge is  $\sim 17$  km thick, which consist of 2 km thick volcanic rocks as surface load, 6 km thick oceanic crust and 9 km thick underplated magmatic rocks as subsurface load. While the gravity model across the northern part of the ridge shows that the ridge was emplaced on continental crust with a thickness of about 20 km. About 3 km thick volcanic rocks were emplaced as surface load on top of the crust, which seems to have contributed to flexure of the crustal layers and Moho boundary to the magnitude of about 3 km. The results further suggest that the

southern part of the ridge was emplaced on relatively weak oceanic lithosphere, while the northern part was emplaced on continental lithosphere.

4. The east side of the Comorin Ridge all along is controlled by different tectonic elements, southernmost part by the 79°E FZ, central part by the COB and northernmost part by termination of the Gulf of Mannar Basin. Gravity model studies have determined relatively thin (~ 21 km) continental crust on western margin of Sri Lanka, which may have evolved due to the crustal stretching during the rift processes that took place during the breakup of eastern Gondwanaland fragments and early spreading activity.
5. The present results of the Comorin Ridge together with published plate kinematic models of the north Indian Ocean led to infer that the Comorin Ridge was evolved at about 90 Ma during the rift stage of the Madagascar from the southwest of India.

## **7.2 The Structure and Evolution of the 85°E Ridge**

The 85°E Ridge extends for about 2500 km long from the Mahanadi Basin in the north to the Afanasy Nikitin seamount in south in the Central Indian Basin. The ridge associates with two contrasting gravity anomaly signatures: negative anomaly over the north part (up to 5°N latitude), where the ridge structure is buried under thick Bengal Fan sediments, and positive anomaly over the south part, where the structure is intermittently exposed above the seafloor. Origin of the 85°E Ridge is enigmatic due to its characteristic negative gravity anomaly and complex magnetic signatures. In this study, the morphology, trend, extent, and characteristic negative gravity anomaly signature are studied in detail using seismic reflection, satellite and ship-borne gravity data. The ridge structure and isostasy aspects are further investigated using process oriented modeling of gravity and seismic reflection data. The important conclusions of this study are as follows.

1. The 85°E Ridge extends from 19°N to 5°S with variable widths range from 100 to 180 km. The width of the ridge is greater in the vicinity of 14°N latitude and this part is associated with a significant gravity low of ~ 80 mGal. Further north between 15°N and 16.5°N latitudes, the gravity anomaly of the ridge is not apparently clear, but reappears anomaly signature again near 17°N latitude and continues further north up to 19°N, in to the region of offshore Mahanadi Basin. Towards south between 11°N and 2°N, the ridge track turns in clockwise direction, then continues straight-down to join the Afanasy Nikitin seamount (ANS). The prominent negative gravity anomaly signature associated with the 85°E Ridge in the Bay of Bengal region changes to positive south of 5°N and in further south, the ANS is associated with significant positive gravity anomaly.
2. Seismic reflection sections crossing the 85°E Ridge in the Bay of Bengal region suggests that the subsurface disposition of the ridge is quite variable. The ridge topography has a steep westward throw and gentle eastward dip at 13°N latitude and appears as a double peaked basement rise at 14°N, whereas at 14.7°N the relief of the ridge is much less with eastern side of the ridge dominated by a prominent basement high probably associated with a oceanic fracture zone. Gravity anomalies along these sections show that the ridge is associated with a prominent negative gravity anomaly (~50 mGal) flanked by regional gravity highs on either side. In the south, the morphology and gravity anomaly signature of the ridge structure are distinctly different in comparison to the sections of the Bay of Bengal. Along 4.5°N latitude, the ridge is characterized by shallower basement and exposed above the seafloor with a prominent positive gravity anomaly of 40 mGal amplitude.
3. Process oriented modeling of seismic and gravity data of the 85°E Ridge revealed that the ridge was emplaced on a lithosphere, whose elastic plate thickness was approximately 10-15 km and suggest the off-ridge tectonic emplacement. This result is consistent for both northern and southern parts of the ridge in spite of contrasting gravity signatures associated with the ridge.

4. The isostatic model of the 85°E Ridge suggests that the ridge structure and the overlaying sediments are supported by a broad flexure of the Moho boundary. Two-dimensional gravity forward modeling also suggests flexural compensation beneath both northern and southern parts of the ridge. The gravity models derived by both the methods conclusively suggest that the negative gravity anomaly over the 85°E Ridge could be explained by a combination of sources: the flexure at Moho boundary, thick Bengal Fan sediments over the ridge and the presence of high density metasedimentary rocks on both sides of the ridge flanks.
5. The gravity anomalies of the 85°E Ridge are reconstructed since the ridge formation with possible crustal structures prevailed at different geological ages. At the time of ridge emplacement, that is during the late Cretaceous the ridge was associated with a significant positive anomaly with a compensation generated by a regional flexure of the Moho boundary. By early Miocene the ridge was approximately covered by post-collision sediments and led to alteration of initial gravity anomaly to a small positive anomaly. At present, the ridge is buried by approximately 3 km thick Bengal Fan sediments on its crestal region and about 8 km thick pre- and post-collision sediments on the ridge flanks. This geological setting had changed physical properties of the sediments and led to alter the minor positive gravity anomaly of early Miocene to distinct negative gravity anomaly.
6. Present results together with published plate reconstruction constraints suggest that the 85°E Ridge was emplaced by a short-lived hotspot from 85 to 55 Ma in an intraplate geological setting.

### **7.3 The Structure and Tectonics of the Ninetyeast Ridge**

The Ninetyeast Ridge is one of the classic aseismic ridges of the World Oceans and probably the longest linear feature on planet Earth. It stretches for more than 5000 km in the eastern Indian Ocean from 30°S to 17°N approximately along the 90°E meridian. The Ninetyeast Ridge was emplaced on the Indian plate during its northward drift between the

late Cretaceous and early Cenozoic by the Kerguelen hotspot volcanism. In this study, an attempt was made to understand the isostatic compensation mechanisms along the Ninetyeast Ridge using flexural modeling and admittance analysis of closely spaced bathymetry and gravity profiles. Further, two-dimensional gravity forward modeling was carried out along five representative profiles of different parts of the ridge in order to determine the crustal structure of the ridge. The important conclusions of this study are as follows

1. Elastic plate thickness ( $T_e$ ) of the Ninetyeast Ridge between latitudes  $28^{\circ}\text{S}$  and  $8^{\circ}\text{N}$  has been determined using flexural modeling and admittance analysis of 72 gravity and bathymetry profiles distributed at approximately equal interval. The results suggest that, southern (south of  $18^{\circ}\text{S}$ ) and northern (north of  $2^{\circ}\text{N}$ ) parts of the ridge are flexurally compensated with elastic plate thickness values of  $>10$  and  $>18\text{km}$ , respectively. Admittance analysis further suggests that the central part ( $20^{\circ}\text{S}$  to  $2^{\circ}\text{N}$ ) of the ridge has Airy type compensation with crustal thickness of 15-20 km. However,  $T_e$  values derived in flexural modeling of the profiles revealed that that central part of the ridge may further divided into 1) south-central part ( $18^{\circ}\text{S}$  to  $8^{\circ}\text{S}$ ), where the  $T_e$  values constantly decreases from 20 km to 5 km and 2) north-central part ( $8^{\circ}\text{S}$  to  $2^{\circ}\text{N}$ ), where  $T_e$  values randomly varies between 2 and 25 km.
2. Crustal structure of the Ninetyeast Ridge are determined using two-dimensional gravity forward modeling along five east-west gravity profiles, representing from different parts of the ridge possesses variable elastic plate thickness values, under the constraints from seismic results, particularly from the point of corroboration of ridge variable isostatic compensations. The models suggest that the crustal structure of the Ninetyeast Ridge show considerable internal variations. In the southern part along  $\sim 26^{\circ}\text{S}$  latitude, the ridge topography is compensated by down-flexing of crustal layers 2A, 2B and 3A with amplitude of about 2.5-3 km. In the south-central part ( $\sim 13.5^{\circ}\text{S}$ ), the model suggests very thick crust ( $\sim 20$  km) beneath the ridge, which includes  $\sim 10$  km thick underplated body. In north-central part gravity models at  $3^{\circ}\text{N}$  suggest thickening of crust beneath the ridge topography, in contrast at  $4^{\circ}\text{N}$  the ridge shows a

different crustal structure, where the volcanic load is supported by down-flexing of crustal layers. These crust mantle configuration derived from the two-dimensional gravity forward modeling is in good agreement with the  $T_e$  values obtained along the respective profiles.

3. Over the north part of the Ninetyeast Ridge, where the ridge structure is buried under the Bengal Fan sediments, the model results suggest that the volcanic load (ridge material) is compensated by a broad flexure of the crustal layers with wavelengths greater than that of the ridge. The model also suggests the presence of low-density mantle rocks of ~ 4.5 km thick beneath the ridge. The model results are fairly in good agreement with the results of admittance analysis of the northern part of the ridge, and they together obviously suggest the flexural compensation with both surface and subsurface loading. The depth to the buoyant load ( $z$ ) derived from the admittance analysis matches well with the depth to the low-density mantle rocks in the model.
4. Based on present results and available plate reconstruction model results a plausible tectonic model is proposed for the formation of Ninetyeast Ridge. The southern part of the ridge was emplaced on a lithosphere of intermediate strength possibly along the edge of the Indian plate, whereas the northern part was emplaced clearly in an intraplate setting. The highly variable isostatic compensation mechanisms in the central part of the ridge could be a manifestation of the complex interactions of the Kerguelen hotspot and Wharton spreading ridge segments. The north-central part may have emplaced on a crust of highly variable age produced by multiple southward ridge jumps, whereas the south-central part was emplaced on a crust of uniformly increasing age produced as a result of a major southward ridge jump.

## 7.4 Future Research

During the investigation of present research problems, particularly understanding the isostatic compensation mechanisms beneath three important aseismic ridges: Comorin Ridge, 85°E Ridge and Ninetyeast Ridge, it is found that there are some interesting



research aspects related to the evolution of the ridges. Those aspects, mentioned below, may further be investigated in future research for better understanding.

#### **7.4.1 Continent-Ocean Boundary on Western Margin of Sri Lanka and Southern Tip of India**

Demarcation of Continent-Ocean Boundary (COB), crustal structure, stretching rates during the margin evolution, etc., along the passive continental margins provides useful geological information on creation of early oceanic crust, evolution of rifted and deep water basins, ridges, etc. The COB and associated geophysical anomaly signatures may further reveal how the segments of continental margin split from its conjugate margin, whether those were in transform motion before they complete the rifting and imitates drifting or in normal rift phase for longer periods. It was discussed in Chapter 4 that, the northern part of the Comorin Ridge was emplaced on rigid continental lithosphere and the central part was evolved nearly in the vicinity of continent-ocean adjoining region and the southern part on a weak oceanic crust. Based on this study, the COB on the ridge and off western margin of Sri Lanka and southern tip of India were cautiously demarcated. However, exact demarcation of COB in this region is an important geophysical constraint, which can provide new insights to the rifting history of Sri Lanka from the Indian landmass and formation of the Mannar Basin in between.

Admittance analysis of gravity and bathymetry profiles of the continental margin regions of southern India and western margin of Sri Lanka may also provide constraints associated with continental rift processes. Further, flexural backstripping analysis of seismic reflection profiles from the Mannar Basin may be used to understand the basin evolution and demarcation of the COB. This is particularly interesting to the oil industries in view of the hydrocarbon prospects of the basin.

#### **7.4.2 Origin of the 85°E Ridge**

In the present study, crustal structure and isostatic compensation mechanism of the 85°E Ridge are determined using process oriented modeling of gravity and seismic reflection

data. The derived results of the ridge together with previously published geophysical results led to interpret that the ridge was emplaced by volcanic activity. However, following the analogy of the negative gravity anomaly signature of the Laxmi Ridge in the Arabian Sea and its continental sliver interpretation, it may also be possible to think in the direction of assigning continental origin to the 85°E Ridge. Deep seismic refraction studies may possibly resolve this ambiguous issue and lead to better understanding of the nature of the ridge.

The present study further suggests that the 85°E Ridge was emplaced by a hotspot in an intraplate geological setting. However, several issues related to the ridge evolution are yet to be understood very clearly such as, which hotspot was responsible for the emplacement of the 85° E Ridge? What is the exact timing of the emplacement? Why the clock-wise turn exists in the ridge track? etc. Some of the researchers believe that the ridge was emplaced by the Crozet hotspot (Curry and Munasinghe, 1991), while others opine that it is a product of the Kerguelen hotspot (Bastia et al., 2010). In the later case, the extension of the ridge towards Rajmahal Traps needs to be established by geophysical and geochemical studies. Also, a plate reconstruction model, which allows emplacement of both the 85°E Ridge and the Ninetyeast Ridge, needs to be developed and tested. In unison, integrated geophysical and geochemical studies are essential to be carried out to unravel the complexities associated with the origin of the 85°E Ridge.

#### **7.4.3 Variable Isostatic Compensation Mechanisms beneath the Ninetyeast Ridge and its Complex Tectonic Evolution**

As discussed in Chapter 6, the isostatic response of the Ninetyeast Ridge all along its track is highly variable, especially in the central part of the ridge. This is interpreted as a product of interaction between hotspot and spreading centers and also with multiple ridge jumps beneath the Ninetyeast Ridge during the evolution of the ridge. In other words, whenever the spreading centre reached a critical distance away from the hotspot, the spreading centre moved towards the hotspot by southward ridge jump. Although recent geophysical studies of the Ninetyeast Ridge support the idea of southward ridge jumps (Sager et al., 2010; Krishna et al., 2011b), the dynamics involved in the process are yet to

be known clearly. The Ninetyeast Ridge is a unique feature and provides the opportunity to study the ridge-plume interactions, which have great implications in global plate tectonics.

The role of the 89°E FZ in the emplacement process of the Ninetyeast Ridge is another important geophysical aspect. This fracture zone, which bounds the eastern edge of the southern part of the Ninetyeast Ridge crosses the ridge at about 11°S, and thereafter borders the western edge of the ridge towards north. Interestingly, this ridge-fracture zone junction separates the north-central part, which was emplaced on a crust produced by multiple southward ridge jumps from the south-central part, which was emplaced on a crust produced as a result of a major southward ridge jump. How the 89°E FZ acted as a thermo-mechanical boundary for the volcanic outpour of the Kerguelen hotspot need to be further investigated.

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## **List Publications from the Present Research Work**

Sreejith, K.M., Krishna, K.S. Bansal, A.R., 2008. Structure and isostatic compensation of the Comorin Ridge, north central Indian Ocean. *Geopy. J. Int.*, 175, 729-741.

Sreejith, K.M., Radhakrishna, M., Krishna, K.S., Majumdar, T.J., 2011. Development of the negative gravity anomaly of the 85°E Ridge, northeastern Indian Ocean – a process oriented modeling approach. *J. Earth Syst. Sci.* (in press).

Sreejith K.M., Krishna, K.S., 2011. Structure and isostasy of the Ninetyeast Ridge and its tectonic implications. (Under preparation).